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A MATHEMATICAL MODEL FOR EVALUATING FLUIDIZED BED COMBUSTION EFFICIENCY OF OIL SHALE

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МАТЕМАТИЧЕСКАЯ МОДЕЛЬ ДЛЯ ОЦЕНКИ ЭФФЕКТИВНОСТИ ГОРЕНИЯ ГОРЮЧЕГО СЛАНЦА В КИПЯЩЕМ СЛОЕ

Abstract

Carbon combustion efficiency is one of the significant parameters to evaluate the operational performance of fluidized bed boiler for burning oil shale. In this paper, a mathematical model was developed which consists mainly of single-particle oil shale combustion kinetics and residence time distribution function of oil shale with different particle sizes (0—10 mm). On the basis of oil shale combustion kinetic parameters and operation variables, the model was used to calculate the carbon combustion efficiency of Maoming fluidized bed boiler with a capacity of 35 t/hr. The obtained results indicate that the model gives a good agreement with the organic carbon analysis data in oil shale ash from fluidized bed combustion boiler.

I. Introduction

In recent years, much attention has been paid to energy sources and environmental protection in the world. In order to utilize coal resource sufficiently and to reduce environmental pollution efficiently, fluidized bed combustion technology (FBC) has been widely used in power plants for burning coal. FBC has all the advantages of conventional combustion technology plus some additional benefits. In FBC units, due to relatively low temperature, NO_x emission can be greatly reduced. In addition, the mixture of limestone or other sorbents in the combustion bed will result in the capture of SO_2 in flue gas. Another advantage of FBC is to make the combustion of low grade solid fuels possible because of longer residence time for combustion. Therefore, fast development of FBC has been achieved. And a lot of fundamental research work has been performed on FBC for coal combustion.

In Fushun and Maoming, China, different scale FBC plants for burning oil shale have been built in order to meet the need of local power supply. In these plants, particulate oil shale ($<$8 mm in diameter) is used as feedstock which cannot be utilized in the present oil shale lump retorts and has been discarded for many years. After several trial operations, preliminary success has been made in Maoming oil shale fluidized bed boiler, but further improvements should be done. On the other hand, Maoming Petroleum Industry Corporation is planning to import FBC technology from abroad to build a large power station for burning oil shale. However, basic investigations on FBC for oil shale combustion are scarcely found in the literature at home and abroad up to now. So, it is neccessary to carry out fundamental studies on oil shale fluidized bed combustion. The fundamental information and the analysis of existing processes are important for the improvement of present boiler, for the design of new type boiler, as well as the understanding of imported technology. The objective of this study is to develop a mathematical model by using experimental data and operation variables of oil shale fluidized bed combustion boiler. The model will be used to calculate the combustion efficiency of FBC for oil shale and then to evaluate the operational performance of the boiler.

II. Mathematical Model

1. Residence time distribution.

According to the literature [1], residence time distribution of a solid particle in fluidized bed can be shown below:

$$E(t, d) = \frac{1}{\bar{t}(d)} \exp[-t/\bar{t}(d)] \qquad (1)$$

where $E(t,d)$ — residence time distribution function (s^{-1})
d — particle diameter (cm)
t — residence time (s)
$\bar{t}(d)$ — average residence time (s), its expression is written as follows;

$$\bar{t}(d) = W/[F + W \cdot K(d)] \qquad (2)$$

where F — oil shale feed (Kg/s)
W — stationary bed weight (Kg)
$K(d)$ — entrainment coefficient of particle (s^{-1}), defined as the ratio between weight of entrained particle and weight of same size particle in the bed.

2. Particulate oil shale combustion kinetics

Fast combustion kinetics of Fushun and Maoming oil shale particle has been investigated to simulate the behaviour of fluidized bed combustion for oil shale [2]. The results indicate that fluidized bed combustion of oil shale mainly takes place in two stages. The first stage belongs to fast heating combustion, which can be characterized by oil shale pyrolysis kinetics. In other words, oil shale is at first subject to pyrolysis to produce volatiles, and the volatiles are burned in gas phase. The second stage is isothermal combustion of oil shale char at a constant temperature (i.e. operation temperature of bed). According to the previous study [3], at fast heating step, relationship between organic carbon conversion and temperature can be shown below:

$$X(t) = 1 - \exp[-\frac{ART^2}{\beta E}(1 - \frac{2RT}{E})\exp(-\frac{E}{RT})] \qquad (3)$$

where A — pre-exponential factor (s^{-1})
E — apparent activation energy (J/mol)
R — gas constant ($R = 8.314$ J/mol.K)
T — reaction temperature (K), ($T = T_0 + \beta t$)
$X(t)$ — organic carbon conversion for oil shale combustion at time t, i.e. carbon combustion efficiency
β — heating rate (K/s)

In second combustion step, isothermal combustion of oil shale particle can be described by using shrinking core reaction model with three resistances. The three resistances involve gas film diffusion, ash layer diffusion and chemical reaction. Its expression can be written below [2, 4]:

$$t = d\varrho_c/72C_{Ag}\{d/4D_e[1 + 2(1 - X(t)) - 3(1 - X(t))^{2/3}] + X(t)/K_f + [3 - 3(1 - X(t))^{1/3}]K_g\} \tag{4}$$

where C_{Ag} — O_2 concentration in gas phase (mol/cm^3)
D_e — effective diffusivity of O_2 in ash layer (cm^2/s)
K_f — gas film mass transfer coefficient (cm/s)
K_g — reaction rate constant (cm/s)
ϱ_c — organic carbon density of oil shale particle (g/cm^3)

It is clear that equation (4) is an implicit function for carbon conversion *X(t)*. Hence, a trial-and-error method will be needed to obtain *X(t)*.

3. Weighted average of carbon conversion

The conversion *X(t)* calculated by equations (3) and (4) is the function of individual particle diameter *d*. So, particles with different diameters will result in different conversion values. Even if the same size particle is considered, different results may be obtained, which depends on the residence time distribution of a certain size of oil shale particle. Therefore, combustion conversion of oil shale with the same particle size has to be determined by weighted average using residence time distribution function. The expression is below:

$$\bar{X}(d) = \int^{\infty} E(d, t) \cdot X(t)dt \tag{5}$$

$\bar{X}(d)$ represents weighted average of conversion for the certain particle sizes. *E(d,t)* and *X(t)* are given in equations (1), (3) and (4). It should be pointed out that the integration of equation (5) must be made in two regions due to two *X(t)* expressions involved.

The conversion $\bar{X}(d)$ from equation (5) is a function of particle diameter *d*. Because oil shale particles with different sizes (0—10 mm) were used as the feedstock of fluidized bed boiler, an overall averaged conversion (efficiency) will be calculated to estimate the combustion efficiency of oil shale. The equation can be written as follows:

$$\bar{X} = \sum_{i=1}^{n} X(d_f) \cdot Y(d_f) \tag{6}$$

where X — overall averaged conversion, i.e. organic carbon combustion efficiency;
$Y(d_f)$ — weight fraction of feedstock with diameter d_f;
n — there are n different particle sizes involved in feedstock (in this study, taking $n = 12$).

III. Data and Results

In order to apply the mathematical model to fluidized bed combustion boiler, the operation variables of units are given in Table 1.

The sieve analysis data concerning fly ash, overflow ash and oil shale in the bed are listed in Table 2 respectively. It is noted that the data for oil shale in the bed were calculated by weight average of overflow ash and fly ash.

Table 1. **Some operation variable from Maoming oil shale fluidized bed combustion boiler with a capacity of 35 t/hr**
Таблица 1. **Параметры работы котла производительностью 35 т/ч для сжигания горючего сланца в кипящем слое**

Oil shale feed, t/hr	Shale ash, t/hr	Overflow ash, t/hr	Fly ash, t/hr	Stationary bed weight, kg	Bed temp., °C	Bed bulk density, kg/m^3	Stationary bed height, m	Bed area, m^2	Shale carbon content, wt,-%	Ash carbon content, wt.-%
23.333	14.9	5.0	9.9	4365	800	614	0.526	13.5	17	0.83

Table 4. **Combustion conversion (efficiency) of Maoming oil shale**
Таблица 4. **Конверсия (эффективность) горения горючих сланцев месторождения Маомин**

	Particle diameter, mm											
	0.045	0.076	0.10	0.15	0.23	0.32	0.75	1.50	2.50	4.0	6.0	9.0
$K(d)$, s^{-1}	0.00184	0.00170	0.00161	0.00149	0.00141	0.00131	0.00088	0.00059	0	0	0	0
$\bar{t}(d)$, min	6.00	6.27	6.54	6.78	7.12	7.48	9.12	10.84	17.57	17.57	17.57	17.57
$\bar{X}_1(d)$	0.814	0.771	0.762	0.749	0.735	0.723	0.693	0.668	0.648	0.630	0.613	0.596
$\bar{X}_2(d)$	0.160	0.197	0.205	0.216	0.227	0.235	0.258	0.276	0.294	0.301	0.301	0.301
$\bar{X}(d)$	0.974	0.968	0.967	0.965	0.962	0.958	0.951	0.944	0.942	0.931	0.914	0.897

Table 2. **Sieve analysis data of oil shale and its ash**
Таблица 2. **Данные ситового анализа горючего сланца и пыли**

	Particle diameter, mm											
	0.045	0.076	0.10	0.15	0.23	0.32	0.75	1.5	2.5	4.0	6.0	9.0
Fly ash, wt.-%	2.31	1.68	3.67	3.63	16.17	30.25	36.17	6.14	0	0	0	0
Overflow ash, wt.-%	0	1.10	0.45	1.80	—	4.92	24.78	20.62	6.81	15.13	12.10	12.30
Oil shale in bed, wt.-%	1.54	1.49	2.60	3.02	10.78	21.81	32.36	10.97	2.27	5.04	4.33	4.10

Table 3. **Combustion kinetic parameters for Maoming oil shale particle**
Таблица 3. **Кинетические параметры горения для частицы горючего сланца месторождения Маомин**

E, J/mol	A, s^{-1}	K_f, cm/s	K_g, cm/s	D_e cm^2/s	ϱ_c g/cm^3	C_{Ag} mol/cm^3	β, °C/s	R, J/mol.K
54 883	793	4.15	222	0.15	0.16	3×10^{-6}	6.5	8.314

The kinetic parameters of Maoming particulate oil shale combustion are shown in Table 3 [2].

On the basis of data in Table 1 to 3, oil shale combustion conversion can be calculated by using developed model, i.e. equations (1) to (6). The results are shown in Table 4. The main calculation steps are as follows:

(1) To calculate entrainment coefficient $K(d)$ of different particle sizes by using the known data in Tables 1 and 2.

(2) To determine the average residence time $\bar{t}(d)$ as a function of particle diameter by means of equation (2).

(3) To obtain the expression of the residence time distribution function $E(d,t)$ by using equation (1) and the known results of $\bar{t}(d)$.

(4) To calculate the combustion conversions, which are different for the different oil shale particle diameters, by using equations (3) to (5).

(5) To calculate the combustion efficiency of oil shale by using equation (6) and data in Table 2.

In Table 4, $\bar{X}_1(d)$ and $\bar{X}_2(d)$ represent oil shale combustion conversion in fast heating stage and at constant temperature stage respectively, while $\bar{X}(d)$ is total combustion conversion, $\bar{X}(d) = \bar{X}_1(d) + \bar{X}_2(d)$, as a function of particle diameter. If conversion $\bar{X}(d)$ will be averaged over total diameter range (0—10 mm), the overall combustion efficiency equal 95.1 %. The result corresponds to 0.85 % in terms of organic carbon content in shale ash, which is identical with its analysis data for boiler's shale ash (0.83 %, see Table 1).

IV. Conclusions

Several major conclusions are as follows (as shown in Table 4):

1. A larger oil shale particle size results in a longer average residence time.

2. Fast heating stage contributes about 60—80 % of total combustion of oil shale, which is different due to different particle size.

3. Overall averaged combustion conversion (efficiency) $\overline{X}(d)$ decreases from about 97 % to 90% with the the increase of particle size.
4. Model prediction for overall combustion efficiency gives a satisfactory agreement with the operation data, which indicates a successful application of the model to the evaluation of oil shale fluidized bed combustion process.
5. Further investigations are needed to improve the model, particularly, in the residence time distribution function.

РЕЗЮМЕ

Предлагается математическая модель для оценки эффективности сжигания горючего сланца в кипящем слое.

В последнее время названная технология широко применяется для сжигания угля. При этом уменьшается выделение NO_x и SO_2, становится возможным использование низкосортных твердых топлив.

В Китае, в Фушуне и Маомине, имеется несколько установок для сжигания в кипящем слое горючих сланцев. Предлагаемая модель разработана на основании результатов ранее опубликованных исследований, а также экспериментальных данных о работе котла для сжигания горючих сланцев в кипящем слое в Маомине.

Пользуясь этой моделью (уравнения (1)—(6)), на базе данных, представленных в таблицах 1—3, можно определить эффективность (конверсию) сжигания сланца. Соответствующие результаты приведены в табл. 4. На основании её данных делаются следующие выводы:

1. Больший размер частицы обусловливает более продолжительное среднее время её пребывания в кипящем слое.
2. Стадия быстрого нагрева составляет 60—80 % от времени полного горения сланца.
3. Суммарная средняя конверсия (эффективность) горения $\overline{X}(d)$ уменьшается примерно с 97 до 90 % по мере увеличения размеров кусков.
4. Данные об эффективности горения, определенные при помощи модели, удовлетворительно совпадают с результатами эксперимента, что свидетельствует о том, что предлагаемая модель пригодна для оценки процесса горения сланца в кипящем слое.
5. Необходимо продолжить исследования, чтобы обеспечить дальнейшее совершенствование модели, в частности в отношении функции распределения времени пребывания частицы в кипящем слое.

REFERENCES

1. *Kunii D. and Levenspiel O.* “Fluidization Engineering”, John Wiley and Sons Inc., New York, 1969.
2. *Zhang Q. X.* “Study on The Combustion of Particulate Oil Shale”, M. S. Thesis, University of Petroleum, Beijing, 1988.
3. *Li S. Y. et al.* Acta Petrolei Sinica (Petroleum Processing Section), 1986, Vol. 2, No. 3, pp. 1—10.
4. *Wang X. Q. et al.* Proceedings of International Conference on Oil Shale and Shale Oil, Beijing, China, 1988, pp. 495—505.

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